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Keywords: "NASA PROGRAMS" "SUPERSONIC COMBUSTION RAMJET ENGINES" "GROUND TESTS" "WIND TUNNEL TESTS" "ENGINE DESIGN" "FLIGHT TESTS" "ENGINE CONTROL"

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NASA'S HYPER-X SCRAMJET ENGINE GROUND TEST PROGRAM

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Abstract

The final Hyper-X Mach 7 engine flowpath lines were developed using the results of a flowpath development wind-tunnel test program and a series of detailed flowpath analyses, but several questions remain open relative to the effects of facility and/or engine model simulation on the results. Presently this engine flowpath is undergoing an extensive test program to verify its predicted performance and operability prior to the first Mach 7 Hyper-X flight using a series of engine models in several different propulsion wind-tunnels. This test program will measure performance and operability increments on the engine models due to facility effects such as test gas contaminants, low dynamic-pressure simulation, and flow non-uniformity; as well as engine model simulation limitations such as forebody and aftbody truncation, and engine aspect ratio. These measured increments will be compared to increments predicted by the Hyper-X design tools as a verification of the Hyper-X design methodology. This paper will present the Mach 7 verification test program and plans for the Hyper-X Mach 10 and 5 test programs.

Introduction

The Hyper-X Program, NASA's focused hypersonic technology program jointly run by NASA Langley Research Center and Dryden Flight Research Center, is designed to move hypersonic, air breathing vehicle technology from the laboratory environment to the flight environment, the last stage preceding prototype development (Ref. 1). The Hyper-X research vehicle will provide the first opportunity to obtain data on an airframe-integrated, dual-mode, supersonic combustion ramjet (scramjet) propulsion system in flight. These data will provide the first flight validation of wind tunnel test techniques and numerical and analytical methods used to design this class of vehicle. A substantial portion of the Hyper-X integrated vehicle/engine flowpath development, engine systems verification and flight test risk reduction efforts are experimentally based. This paper describes the ongoing scramjet engine ground test program used for engine development and verification to support the Hyper-X flight tests.

The scramjet engine ground test program is comprised of tests of four different engine models in multiple configurations in four propulsion wind tunnel facilities. Nominal test points at Mach 5, 7 and 10 correspond to the original program flight test plans. (The Mach 5 flight test is currently not planned). The objectives for these tests are to directly support the flight tests and to provide data for design methods verification and for ground-to-flight and facility-to-facility comparison. To meet the latter objective, the overall test program is highly integrated and provides numerous comparison tests of different engine models in the same facility, tests with the same engine model in different facilities, and flight. The intent is to isolate differences in a quantifiable manner to provide valuable data on facility effects (such as test gas contaminants, low dynamic-pressure simulation, and flow non-uniformity) and on engine model simulation limitations (such as forebody and aftbody truncation and engine aspect ratio). These measured increments will be compared to increments predicted by the Hyper-X design tools, as a verification of the Hyper-X design methodology.

Integrated Vehicle/Engine Development

The Hyper-X integrated vehicle/engine design process is illustrated in Figure 1. Building on what was learned from previous hypersonic airbreathing vehicle flight test studies (HYFLITE, HySTP, and ALFE, Ref. 1), a flight mission was defined which would satisfy research requirements within program budget and schedule constraints. Based on this study, it was determined that

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a Hyper-X Research Vehicle, HXRV, would be rocket boosted, separate from its booster, and achieve autonomously-controlled hypersonic flight. The HXRV outer mold line, depicted in Figure 1 (upper right), resulted from scaling down the McDonnell Douglas Global Reach Vehicle design (Ref. 2) from its original length of 200 ft. to a length of 12 ft. to meet cost constraints and to make it suitable for the proposed rocket launch system. Adequate vehicle aerodynamic performance was maintained through scaling and thus did not require major redesign. The same was not true for the propulsion flowpath mainly due to scramjet flow physics and thermal/structural design requirements which are not geometrically scalable. Although a substantial database was developed during the NASP program on this class of engine, the reduced scale required specific tailoring of the design for each flight Mach number to provide the required thrust to assure vehicle acceleration. The initial flowpath resulting from the redesign allowed design and fabrication of ground test engines and initiation of detailed flowpath analyses. The integrated experimental and analytical design process depicted in Figure 1 utilizes engine flowpath development tests, analytical design methods, and numerical design methods such as the powered tip-to-tail CFD solution shown in the figure. The process is expected to take multiple iterations as the design evolves. The product is an integrated vehicle/engine flowpath with analytically and numerically determined performance that is adequate to satisfy mission requirements, and also has experimentally-verified engine performance and operating characteristics. The process also provides the experimental and analytical data needed to develop autonomous engine control laws and supports generation of the propulsion contribution to the aero-propulsion database.

This process was implemented starting in the spring of 1996 to support the first Mach 7 flight test (currently planned for early 2000) and led to final Mach 7 engine flowpath lines in the spring of 1997. In March 1999, the integrated vehicle/engine flowpath and propulsion control law verification tests, depicted in Figure 1, commenced. Successful demonstration of the predicted vehicle performance will be considered as validation of the use of the wind tunnel data and CFD in the design process and is the last major step in the design process prior to flight validation. The following sections will describe the propulsion ground test program designed to support this process. First, the Mach 7 engine verification test program, including the propulsion flowpath, integrated aero-propulsion, and engine control law verification tests will be presented. Next, the Mach 10 flowpath development and follow-on verification test program in which testing commenced in May 1999 will be discussed, followed by a brief overview of the Mach 5 engine flowpath development tests.

Mach 7 Engine Flowpath and Control System Verification Tests

Mach 7 engine flowpath and control system verification is being accomplished through a series of tests conducted in several facilities. One of the primary objectives of this extensive test series is to isolate the major differences between the preliminary flowpath development database and the HXRV flight database. The flowpath development data base was generated with the partial-width, truncated fore- and aft-body engine, depicted by the photograph in Figure 1, which was tested at reduced dynamic pressure. A roadmap of the Mach 7 flowpath verification test program is presented in Figure 2, and the differences between the tests are outlined in Table 1. The main elements of this test program are the three engine models, with associated vehicle simulator hardware, and the three test facilities. The engines include the Hyper-X Engine Model (HXEM), the HYPULSE Scramjet Model (HSM), and the Hyper-X Flight Engine (HXFE). The three test facilities (Refs. 3-5) are the 8-Foot High Temperature Tunnel (8-Ft. HTT), the Arc-Heated Scramjet Test Facility (AHSTF), and the Hypersonic Pulse Facility (HYPULSE). These engines and facilities allow an integrated test program to isolate and measure the effects on engine performance and operability caused by the differences between tests. To maintain the correct simulation to flight between tests, Mach number, total enthalpy, and flow angle are matched at the cowl lip plane. (See Ref. 6 for a more complete discussion of propulsion ground test simulation of flight conditions.) The differences between tests exist due to test technique and facility limitations and include facility flowfield uniformity, test gas medium, forebody flowfield and boundary layer, engine aspect ratio, and dynamic pressure. The effect of these differences must be properly accounted for in design and analysis methodologies when using wind tunnel test results as an integral part of vehicle/engine design. In addition, there are two scramjet flight tests that the Hyper-X Program plans to use to contribute to the verification of design tools and test methods prior to the first Hyper-X Mach 7 flight test. These tests, shown in Figure 2, are the CIAM/NASA Mach 6.5 scramjet flight and ground test program, and the proposed University of Queensland Mach 8 scramjet flight and ground test program.

8-Ft. HTT HXEM Tests

Tests of the HXEM provide the bulk of the data required to link flowpath development tests with the complete flowpath tests. The HXEM is a partial-width/truncated length flowpath model that can be tested in the smaller flowpath development facilities, including the AHSTF, but incorporates the same structural design and active cooling as the flight engine to allow testing at full flight dynamic pressure in the 8-Ft. HTT. The model was designed by moving the sidewalls closer together on the flight engine design while retaining most of the design to provide an early verification of the engine thermal and structural design when subjected to the flight test conditions as simulated in the 8-Ft. HTT. Tests of the HXEM in the AHSTF provide a direct comparison with the Mach 7 flowpath development test results. Tests of the HXEM in the 8-Ft. HTT provide engine data at flight dynamic pressure, as well as data in a CH_4-Air-O_2 combustion-heated facility at low dynamic pressure for comparison with the AHSTF results. For the 8-Ft. HTT tests, the HXEM was mounted on the Hyper-X Full Flowpath Simulator (FFS) which provided a partial simulation of the Hyper-X airframe. The three-dimensional geometry of the first forebody ramp of the HXRV, including the correct forebody leading edge radius, flight boundary layer trips, and chine geometry, is replicated by the FFS, as illustrated in Figure 3. Thus, the flow approaching the HXEM simulates the flow in the center of the full-width flowpath. This nearly two-dimensional flow is contained by fences on the second and third forebody ramps before entering the partial-width engine model. The flow exiting the engine is also contained by fences on the initial nozzle expansion and the contoured vehicle nozzle geometry is replaced by a constant-angle expansion surface.

The HXEM is shown (shaded) in its three different configurations in Figure 2. These configurations are required to allow the HXEM to be tested in both the smaller engine development facilities, such as the AHSTF, and the much larger 8-Ft. HTT. During tests in the 8-Ft. HTT, the HXEM was mounted on two configurations of the FFS, one with full boundary layer ingestion and the other with the boundary layer from the Hyper-X forebody simulator diverted, or bled-off. The boundary layer diversion feature of the FFS was used to quantify the effect of full forebody boundary layer ingestion compared to partial boundary layer ingestion encountered with the truncated forebody engines as usually tested in the smaller engine development facilities. For tests in the 8-Ft. HTT, the HXEM/FFS was mounted on a support pedestal and force measurement system as shown in Figure 4. In addition, the HXEM was mounted on a self-contained axial force measurement system within the FFS to obtain high-fidelity measurements of flowpath axial force variations with cowl flap movement and fuel flow level and to obtain a direct force measurement on the HXEM for comparison with tests in other facilities.

8-Ft. HTT HXFE Tests

To provide a complete simulation of the HXRV flight configuration, an additional Hyper-X Flight Engine (HXFE) was manufactured for the purpose of wind-tunnel verification testing in the 8-Ft. HTT. When integrated with the Vehicle Flowpath Simulator (VFS), which contains the full-width forebody and the entire vehicle nozzle, the entire propulsive flowpath is simulated. This configuration, mounted on the same support pedestal and force measurement system as the HXEM/FFS, is shown installed in the 8-Ft. HTT in Figure 5. The HXFE/VFS, shown in detail in Figure 6, incorporates a removable panel encompassing the second and third forebody ramps. Either a flight TPS panel or a more heavily instrumented metal panel can be installed and tested to quantify the effects of the flight TPS (wall temperature and roughness) on engine performance and operability. Survivability and performance of the TPS and the instrumentation installed in it, as well as the flight engine thermal and structural design (including actively cooled leading edges) will be verified.

Simulation of the entire HXRV propulsion flowpath provides a direct link between the flight environment and the 8-Ft. HTT environment and provides data, prior to flight, for verification of the design and analysis tools applied to the flight configuration. These tests also provide valuable data that is difficult to obtain from computations alone. Some examples include transient operation of the engine during inlet starting and the rapid changes in fuel flow rate which are necessitated by the short flight test time. This information is important for the verification of engine control laws and also provides force and moment incremental data during these transient events. Simulations of the Hyper-X flight have demonstrated the need to understand the magnitude of the pitching moment, in particular, during these transients for flight control law development.

Engine Controls Verification

The Propulsion Subsystem Control (PSC) function of the HXRV Operational Flight Program supports the flight experiment by controlling the engine cowl actuation subsystem and the fuel, ignitor, and purge subsystems. Part of the PSC function is to open and close the inlet cowl flap at the beginning and end of the scramjet portion of the flight test, and to control the flow rate of gaseous hydrogen and engine ignitor gas (a mixture of hydrogen and silane) to the engine. The PSC function must provide fuel flow rate control for engine ignition and fuel schedule while compensating for potential variations in the boost trajectory, so that the fuel flow rate to the engine will always be within an acceptable range. Internal engine flowpath pressures are monitored to avoid over-fueling the engine which could cause inlet unstart. The HXEM/FFS and HXFE/VFS tests include "flight-like" subsystems for cowl actuation and fuel and ignitor flow control as well as flight instrumentation on the engine flowpath. These subsystems are controlled by a bench control system hosting a wind tunnel specific version of the PSC software. Although many features of the flight software are not exercised in the wind tunnel tests, partial verification of the flight software in the areas of fuel and ignitor flow control and engine unstart prevention is accomplished. Experience is also gained by analyzing the wind tunnel data with the nominal flight fuel flow schedule.

HYPULSE Tests

The Mach 7 flowpath verification test roadmap in Figure 2 shows two paths leading to flight. The path discussed above leveraged the size and pressure capabilities of the 8-Ft. HTT by testing the complete HXRV propulsion flowpath at full dynamic pressure. The second path leverages the clean air and pressure capabilities of HYPULSE where the HSM, shown in Figure 7, was tested from October 1998 through January 1999. The HSM flowpath is identical to the HXEM flowpath but the two engines have a much different appearance due to the differences in the test environment and test objectives. This engine and facility will be used primarily for the Mach 10 engine flowpath development tests, to be discussed in a later section, but was initially used to provide several important pieces of information on the Mach 7 verification roadmap. Tests of HSM in the HYPULSE facility provided Mach 7 tests at full flight dynamic pressure and enthalpy simulation, comparisons of performance for high-to-low pressure simulations, and a direct, low-pressure comparison of clean-air pulse facility results with arc-heated facility results. In addition, the short test duration alleviates thermal design issues, which facilitates optical access to the scramjet flowpath and allows schlieren and planar images of fuel mixing (Ref. 7) to be acquired. These tests also provide validation of newly developed test techniques used for integrated engine testing in the HYPULSE facility through a comparison of results with tests in continuous flow facilities.

Pre-test Predictions

Part of the verification process of the Hyper-X design tools is to predict the test article performance and operability in the test environment, prior to testing, for comparison with the test data once it is obtained. Resolving differences between the prediction and the test data, if they exist, may require additional higher fidelity analyses or additional tests. Once the differences are understood, the design tools and/or test techniques can be improved as required. Many types of pre-test analyses are performed, ranging from relatively simple methods to three-dimensional Full Navier-Stokes (FNS) CFD. The exact set of pre-test predictions appropriate for each test is determined by the test objectives, the complexity of the flowfields, and the criticality of the results to the success of the flight program. To meet the objectives of the Mach 7 flowpath verification test program, a large set of high level pre-test predictions was completed.

An example of pre-test predictions compared to wind-tunnel data is shown in Figures 8 and 9 for the HXEM tests in the 8-Ft. HTT and the HSM tests in HYPULSE, respectively. Both figures show results from pre-test CFD forebody computations performed on the respective model geometries at the respective test conditions. The computations are compared with data taken from rake-mounted instrumentation probes located upstream of the inlet cowl leading edge. (These rake-mounted probes can be seen installed in the HXEM in Figure 4). Since engine mass capture is a critical performance driver which cannot be directly measured in flight, it is very important to verify that CFD mass capture predictions are accurate on the ground. This is accomplished by comparing the computational results to the detailed instream flow survey data acquired during the wind tunnel tests.

The forebody CFD computations are continued through the inlet and used to anchor performance prediction computations using engine analysis and design tools. Using the same methodology that is used to predict flight performance, computations are performed for each model configuration, test facility, and test condition to verify that the design methods and tools can be used to predict these effects on engine performance. Successful demonstration of this capability also provides verification of the test techniques.

Mach 10 Engine Flowpath Development and Verification Tests

The third flight of the Hyper-X Research Vehicle will be at Mach 10. The Mach 10 flight environment provides many challenges to the design of the scramjet flowpath. Although good integrated performance of the vehicle/engine is the design goal, the severe thermal environment at Mach 10 and the small scale of the HXRV constrain the available design space for the flowpath. To investigate the effects of various flowpath geometric and thermal constraints on integrated vehicle/engine performance, two coordinated design studies were undertaken. One study examined the overall flowpath and the other was focused on the fuel injectors and combustor. Using a statistical Design of Experiments (DOE) approach, a reduced matrix of cases covering a large range of flowpath and injector configurations was analyzed using SRGULL and CFD to predict integrated vehicle/engine performance.

To efficiently perform the computations required for the DOE studies, certain complex phenomena were approximated by simpler analytical or empirical models based on existing information (primarily generated during the NASP program). The results of this study provided a more focused design space for detailed analyses in conjunction with flowpath development ground tests. These design study and test results, along with the constraints imposed by the thermal/structural design studies, will form the basis for the final Mach 10 flowpath. Figure 10 shows a roadmap for the Mach 10 flowpath development and verification tests. The flowpath development tests began in May 1999 using the HSM in HYPULSE. To acquire the required data, the HSM may need to be reconfigured several times. Following the selection of the final Hyper-X Mach 10 flowpath lines, the HSM will be modified, for the verification tests, to match the final flowpath lines; however, it will still be partial width with a truncated fore- and aft-body.

The Mach 10 flowpath verification test series will be more limited in scope than the Mach 7 test series (compare Figure 10 to Figure 2) because of limitations in the size and test time of the HYPULSE facility. This should not impose undue risk to the Mach 10 flight, however, because the combination of the flight data obtained from the first two Hyper-X Mach 7 flights and data obtained from other flight tests (Mach 6.5 CIAM/NASA test and the proposed Mach 8 University of Queensland test program), together with the HYPULSE test program should give a good verification of the flowpath design tools. In addition, because the combustor flow remains supersonic at Mach 10 flight conditions, the empirical design tools relied on at lower speeds to model the complex dual-mode flowfield can be replaced with more sophisticated methods which further reduces design risk. The final Mach 10 flowpath lines will also be subjected to off-design test conditions in HYPULSE to simulate what could reasonably occur during flight. These tests will include angle-of-attack simulation variations, Mach number and forebody shock location variations, dynamic pressure variations, and fueling variations. Throughout the tests the surface, instream probe, and optical measurements (schlieren and a planar fuel plume imaging technique) will be acquired to verify the design calculations. If discrepancies are found between test data and design predictions, contingency Mach 10 flowpath verification tests (see roadmap, Figure 10) can be added to the test program to explore the discrepancies in more detail.

Mach 5 Engine Flowpath Development Tests

Although the originally-planned Mach 5 flight test has been eliminated from the Hyper-X Program, Mach 5 engine flowpath design has continued for the purpose of technology development and to support the possibility of a future Mach 5 flight test. The Hyper-X Mach 5 flowpath development and verification test program is outlined in Figure 11. This roadmap, from flowpath development to flight, is very similar to the Mach 7 roadmap (Figure 2), because many of the same facilities and test techniques can be employed.

The DFX engine and the Arc-Heated Scramjet Test Facility, both of which were used for the Hyper-X Mach 7 flowpath development tests conducted from August 1996 to August 1997, were reconfigured to support Mach 5 tests. To begin the iterative analytical and experimental design process, an initial Mach 5 flowpath was defined using the integrated vehicle/engine development process discussed previously. This flowpath was tested in the AHSTF from April 1998 through August 1998, to provide experimental verification of engine performance and operability.

Before design iterations are incorporated into the DFX for experimental verification, it will be tested in the Combustion-Heated Scramjet Test Facility (CHSTF). As depicted in Figure 11, this will be done to provide direct comparisons of results of the same scramjet engine in different propulsion test facilities. The objective of these comparisons is to assess the various ground test effects such as test gas vitiation and low dynamic pressure on engine performance and operability. The CHSTF is a hydrogen/air combustion-heated propulsion facility which, compared to the AHSTF, can support testing over a greater range of Mach number, dynamic pressure, and angle-of-attack around the nominal Mach 5 condition. Following the facility comparison tests, flowpath development tests will continue with a second iteration. Further iteration will be undertaken as necessary to produce an acceptable final design.

After completion of Mach 5 flowpath development, the original plan was to reconfigure the HXEM engine hardware (used in the Mach 7 verification tests) to perform final Mach 5 flowpath and systems verification tests in the 8-Ft. HTT. However, due to present program constraints and priorities (no Mach 5 flight test), only the initial portion of the Hyper-X Mach 5 flowpath development testing (inside the dashed box on Figure 11) is currently planned.

Summary

This paper discussed the engine flowpath wind tunnel testing portion of NASA's hypersonic technology program, Hyper-X. The Hyper-X Program is designed to elevate scramjet powered hypersonic vehicle technology readiness levels from the laboratory to the flight environment, a necessary step before proceeding to prototype vehicle development. The propulsion wind tunnel program is an integral part of engine flowpath design, flight test risk reduction, and flight vehicle verification. The engine flowpath test programs which were discussed will lead to well characterized, lower-risk, engine flowpaths for the Mach 7 and 10 Hyper-X flight tests and a good baseline engine test series to support a possible Mach 5 flight test program. The flight focus of the program provides a significant challenge to some wind tunnel test techniques, as no airframe-integrated, scramjet-powered vehicle has flown. This focus has also presented the opportunity to design a test program that experimentally isolates the effects of various test techniques on flowpath performance. A better understanding of these effects through the use of design and analysis tools should lead to improvements to these techniques and to the design and analysis tools as well. As a direct result, ground-based experimental wind tunnel techniques, as well as integrated vehicle/engine design methods, are continuing to be improved to meet program objectives. The flight test will provide critical data required to validate design methods, including analytical, computational and experimental methods. Current flight test plans call for the first Hyper-X research vehicle to fly at Mach 7 in early 2000.

Acknowledgements

The authors would like to acknowledge the contributions of the Hyper-X team to this effort. The names are too numerous to list here but include those supporting the test programs with direct test support as well as analytical and numerical support.

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Nomenclature

AOA – Angle-of-attack
AHSTF – Arc-Heated Scramjet Test Facility
ALFE – Air Launched Flight Experiment
CFD – Computational Fluid Dynamics
CH_4 - Methane
CHSTF – Combustion-Heated Scramjet Test Facility
DFX- Dual-Fuel Experimental Parametric Engine
DFRC – Dryden Flight Research Center
DOE – Design of Experiments
FFS – Full Flowpath Simulator
FMS –Force Measurement System

HSM – HYPULSE Scramjet Model
HXEM – Hyper-X Engine Model
HXFE – Hyper-X Flight Engine
HXRV – Hyper-X Research Vehicle
HYFLITE – Hypersonic Flight Experiment
HYPULSE – Hypersonic Pulse Facility
HySTP – Hypersonic Systems Technology Program
LaRC – Langley Research Center
LO_2 – Liquid Oxygen
NASA–National Aeronautics and Space Administration
NASP – National Aero-Space Plane
PSC – Propulsion Subsystem Control
TPS- Thermal Protection System
VFS – Vehicle Flowpath Simulator
8-Ft. HTT - Eight-Foot High Temperature Tunnel

Table 1. Mach 7 Engine Test Matrix.

Engine/Facility	Dynamic Pressure (psf)	Major Test Gas Contaminants	Width	Forebody	Aftbody
HXEM/AHSTF	500	NO	Partial	Truncated	Truncated
HXEM/FFS/ 8-Ft. HTT	650/1000	H_2O, CO_2	Partial	Truncated Via BL Diversion	Truncated
HXEM/FFS/ 8-Ft. HTT	650/1000	H_2O, CO_2	Partial	Full	Truncated
HXFE/VFS/ 8-Ft. HTT	650/1000	H_2O, CO_2	Full	Full	Full
HSM/HYPULSE	500 - 1000	None	Partial	Truncated	Truncated
Flight	1000	None	Full	Full	Full

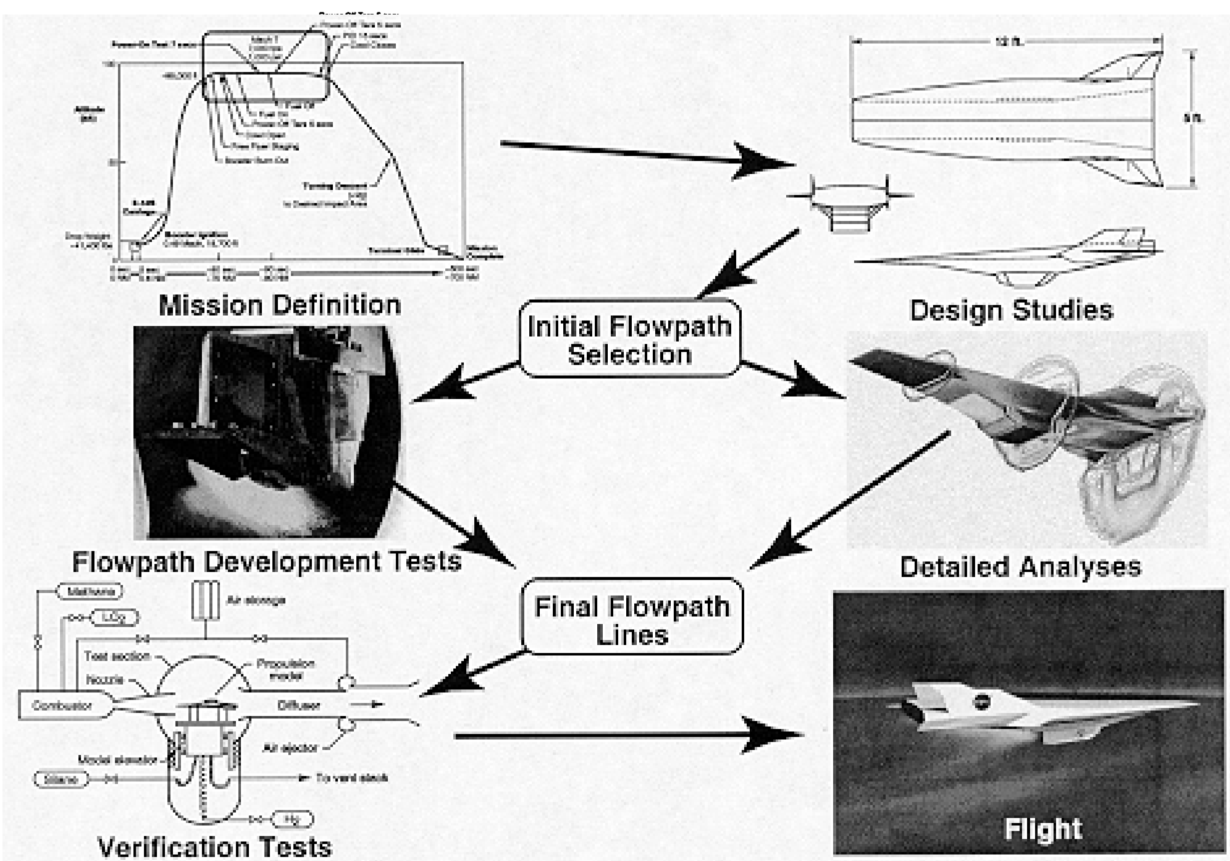

Figure 1. Hyper-X integrated vehicle/engine design process.

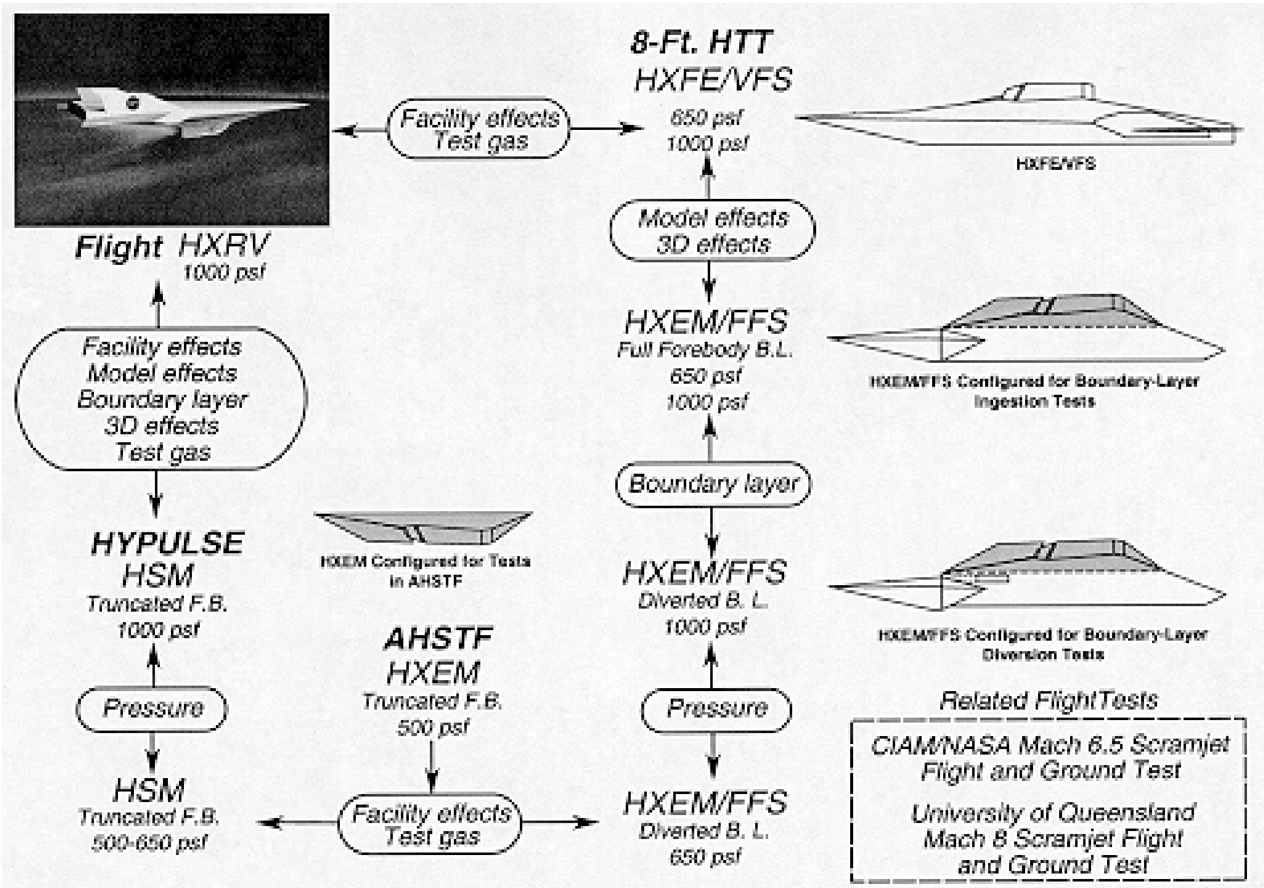

Figure 2. Hyper-X Mach 7 flowpath verification test roadmap.

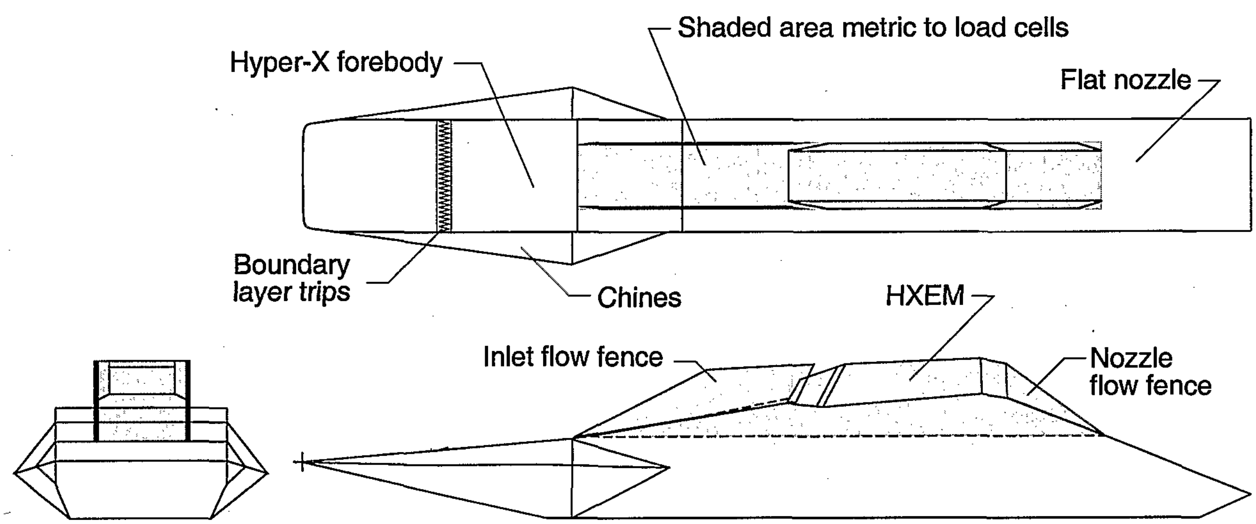

Figure 3. HXEM mounted on FFS.

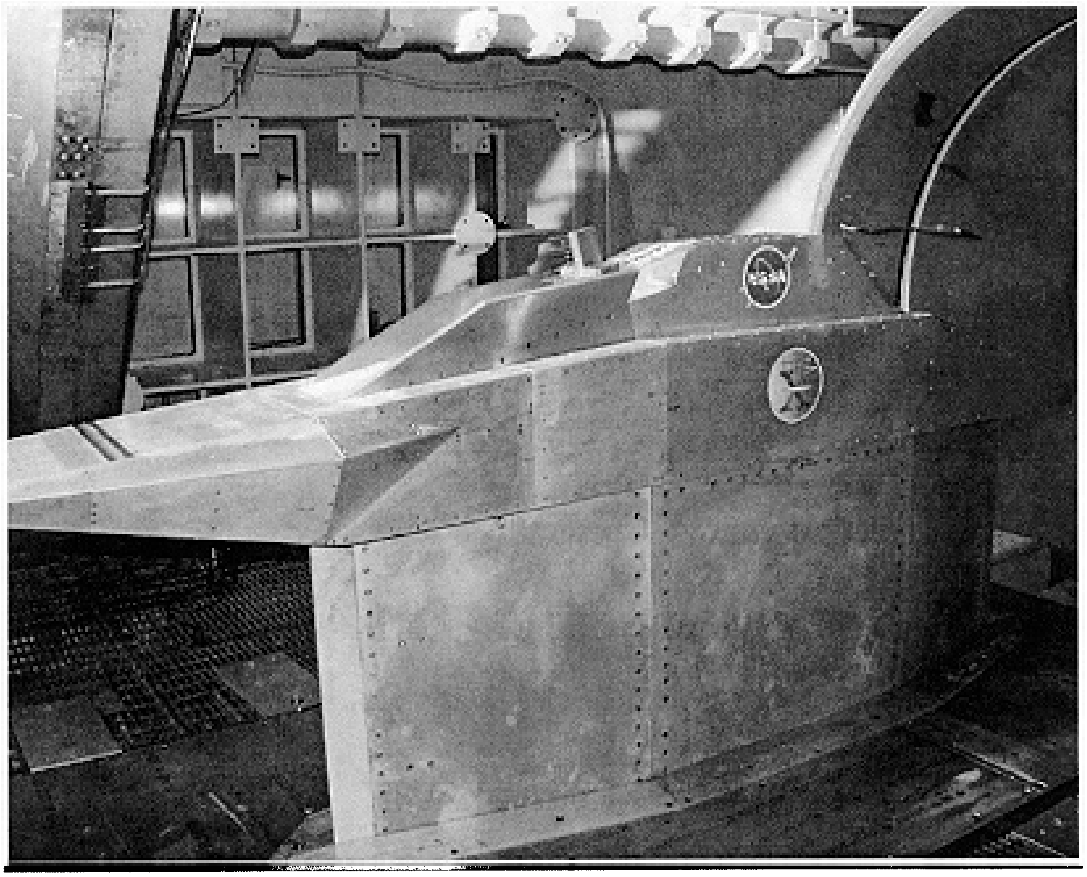

Figure 4. HXEM/FFS mounted in the 8-Ft HTT.

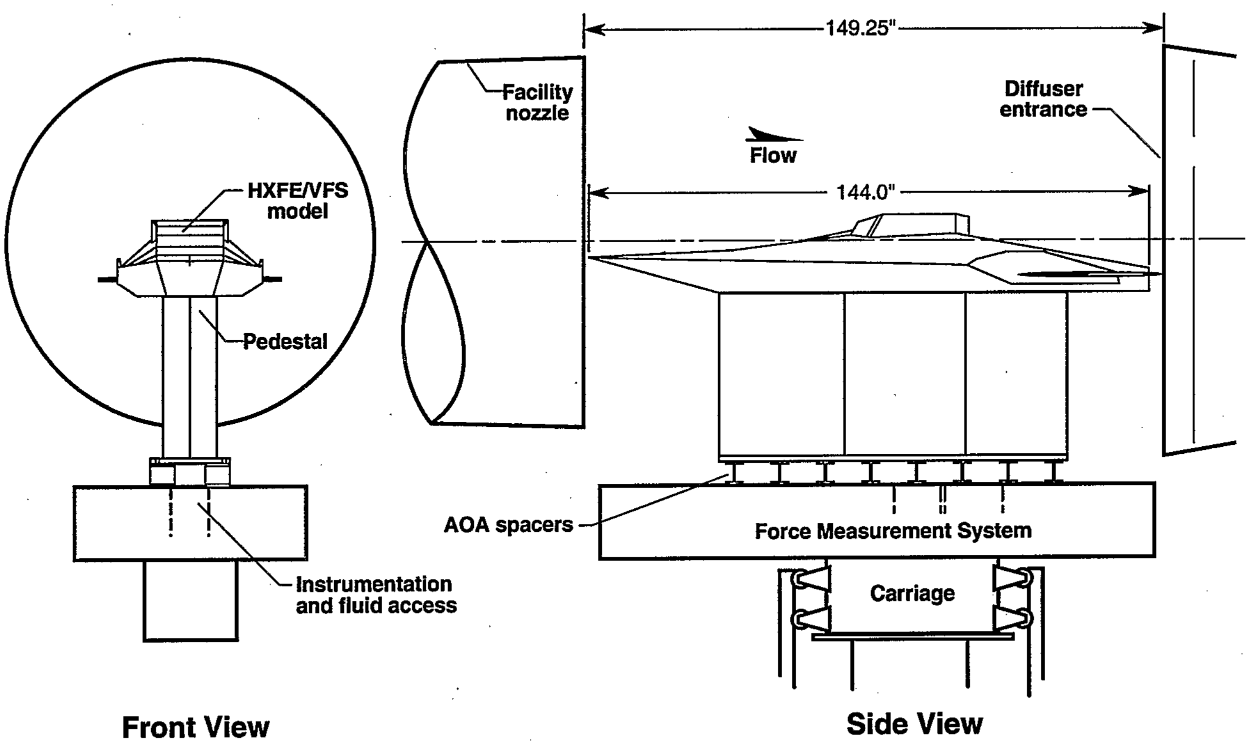

Figure 5. HXFE/VFS in the 8-Ft. HTT.

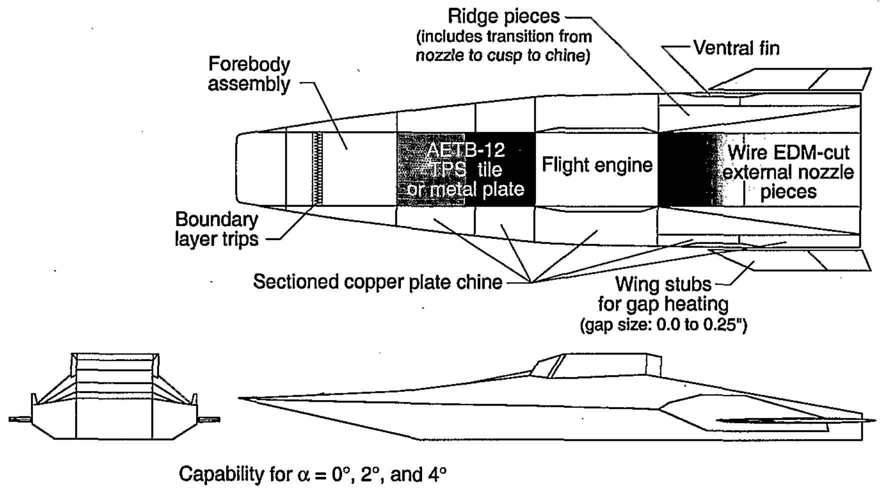

Figure 6. HXFE/VFS details.

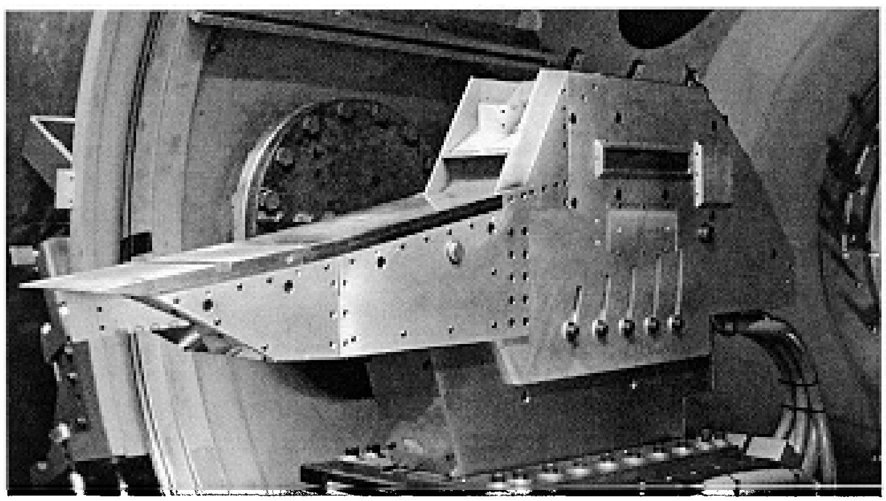

Figure 7. HSM mounted in the HYPULSE facility.

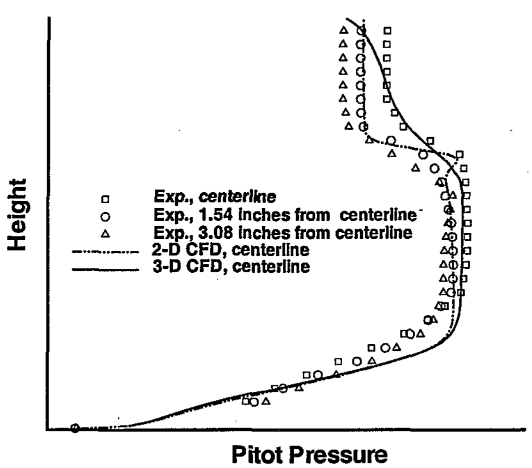

Figure 8. Pretest CFD calculations of pitot pressure compared to data for HXEM tests in the 8-Ft. HTT.

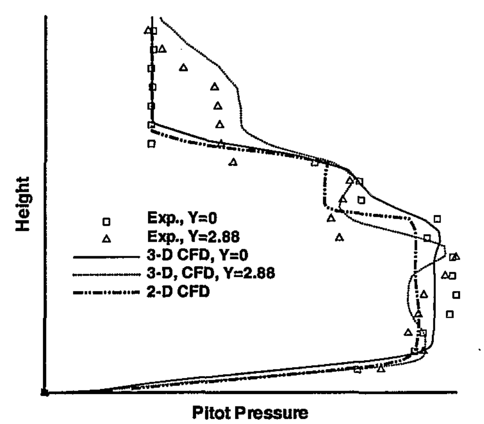

Figure 9. Pretest CFD calculations of pitot pressure compared to data for HSM tests in HYPULSE.

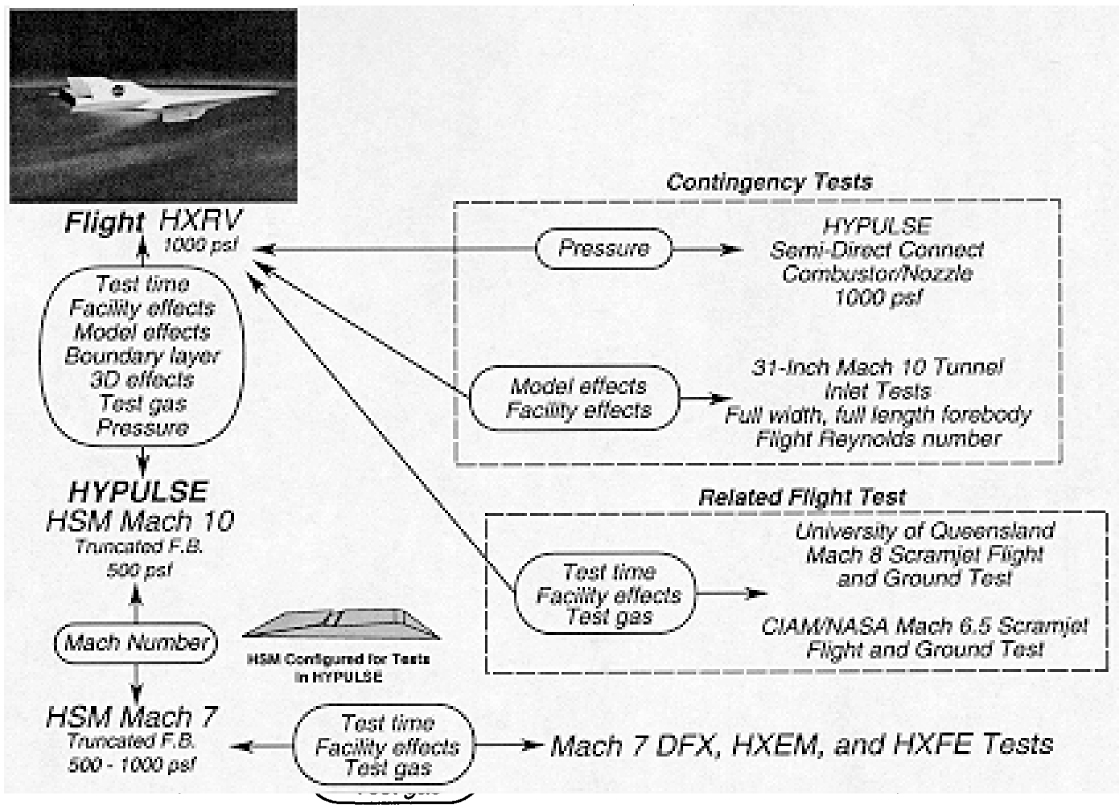

Figure 10. Mach 10 flowpath development and verification test roadmap.

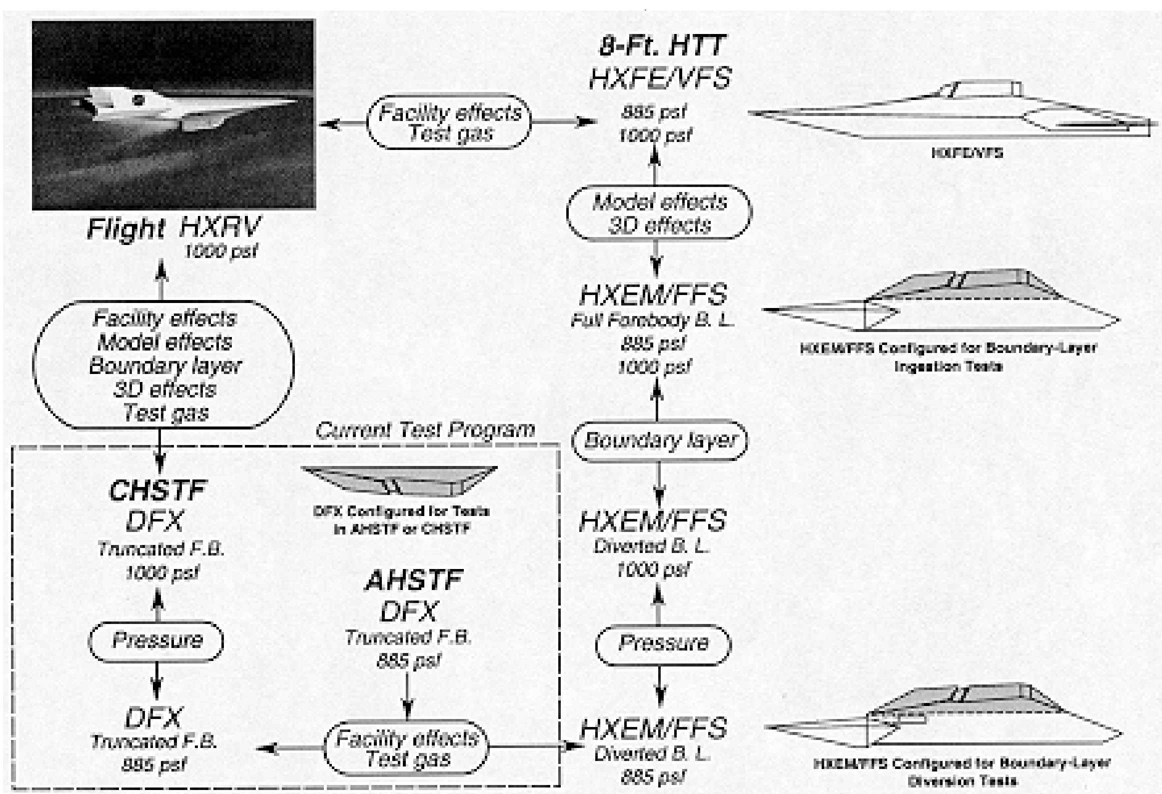

Figure 11. Mach 5 flowpath development and verification test roadmap.